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THE LAKE HURON DATA BASE: CHARACTERIZATION AND USE FOR EVALUATING MULTIFREQUENCY MONOPULSE TRACKING USING A MULTIPATH PROPAGATION MODEL

by

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ABSTRACT

This report has two objectives: (1) to describe in detail a unique multifrequency (8-12 GHz) 32-element array data base collected over Lake Huron and (2) to investigate the experimental performance of multifrequency phase monopulse using a model for specular multipath (called refined monopulse or RMONO because of its use of a "refined" propagation model). Tracking performance is compared with that obtained with phase monopulse averaged over the frequency agile bandwidth and with that obtained with the Refined Maximum Likelihood (RML) algorithm. The results show that for wide agile bandwidth (4 GHz centred on 10 GHz) and adequate number of frequencies (5), RMONO performs almost as well as RML and both perform much better than phase monopulse. However, phase monopulse compares more favorably with a smaller bandwidth (2 GHz) and fewer frequencies (3).

RÉSUMÉ

Ce rapport poursuit deux objectifs soit: (1) une description détaillée d'une base de données plutôt unique obtenue au moyen d'un réseau d'antennes de 32 éléments; les données ont été recueillies sur le Lac Huron à des fréquences variant entre 8 et 12 GHz et (2) d'une mesure de la performance de pistage lorsqu'on utilise plusieurs fréquences avec un monopulse de phase qui inclut un modèle de propagation spéculaire. Le pistage est comparé avec celui obtenu pour l'algorithme RML (Refined Maximum Likelihood) et celui du monopulse de phase utilisant l'agilité en fréquence. Les résultats montrent que pour une large bande de fréquences (4 GHz centrée autour de 10 GHz) et un nombre approprié de fréquences (5), RML et RMONO ont une performance comparable et que les deux algorithmes ont une performance très supérieure au monopulse de phase. Cependant la performance du monopulse de phase se compare plus favorablement lorsqu'on utilise une bande de fréquences plus étroite (2 GHz) et un nombre plus restreint de fréquences (3).

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EXECUTIVE SUMMARY

In late October 1987, a series of experiments were performed on the west coast of the Bruce Peninsula close to Tobermory, Ontario, overlooking Lake Huron. The experiments were designed to acquire real radar data suitable for testing the performance of model-based estimation algorithms. Defence Research Establishment Ottawa (DREO) used the data to evaluate the performance of the Refined Maximum Likelihood (RML) algorithm. A 32-element sampled aperture antenna developed by the technical staff at the Communication Research Laboratory, McMaster University, was used to collect data. The data were collected using multiple frequencies within the 8 to 12 GHz band; this data base appears unique in terms of its wide frequency range, number of elements in the array and the rough sea conditions under which it was collected. Considerable interest in this data has been expressed by scientists in several countries.

The first part of this report provides a description of the data format, data quality and calibration procedures required by such users. The second part of the report describes a comparative study of the performance of phase monopulse using frequency agility versus that of monopulse using a refined propagation model (RMONO) versus the application of the Refined Maximum Likelihood (RML) method to all 32 outputs of the 32-element array.

The results of the study using the experimental data base are as follows:

1) The most accurate results were obtained by applying RML to the complete 32 element array.

2) Very good results were obtained using RMONO, where the refined propagation model is applied in a maximum likelihood estimation technique to only two outputs: the first output comprising the sum of the upper 16 elements, the second, the sum of the lower 16 elements. RMONO gave results only slightly worse than those given by RML.

3) For a very wide agile frequency bandwidth of 4 GHz and using five frequencies evenly spread over this band, both RMONO and RML performed much better than phase monopulse with averaging over the frequencies. For a smaller bandwidth of 2 GHz and with both 3 and 5 agile frequencies, performance of the three techniques was roughly comparable.

The very good results obtained for RML and RMONO required four or five frequencies distributed over a 4 GHz bandwidth centred about 10 GHz. Fewer frequencies and a smaller bandwidth would require a greater signal-to-noise ratio for good results and would increase the requirements for good calibration. As well, one would expect RMONO to deteriorate more than RML under the above conditions.

The present trend in naval radars is towards active phased-array radars for ship defence. Such systems with their solid-state transceiver modules are able to support a very wide agile bandwidth. The use of RMONO in such a radar system could significantly improve the accuracy of target height estimation in multipath conditions.

In cases where the high precision of RMONO is not required and / or the bandwidth and antenna calibration are not sufficient to support good performance with RMONO, tracking performance may still be significantly improved by averaging monopulse estimates over a number of frequencies within the agile bandwidth.

CONTENTS

THE LAKE HURON DATA BASE: CHARACTERIZATION AND USE FOR EVALUATING MULTIFREQUENCY MONOPULSE TRACKING USING A MULTIPATH PROPAGATION MODEL

1. INTRODUCTION

In late October 1987, a series of experiments were performed on the west coast of the Bruce Peninsula close to Tobermory, Ontario, overlooking Lake Huron. The experiments were designed to acquire real radar data suitable for testing the performance of model-dependent estimation algorithms [1]. The data were also intended for the study of the Refined Maximum Likelihood (RML) algorithm [2-4] developed at Defence Research Establishment Ottawa (DREO) and for the study of adaptive beamforming techniques. A 32-element sampled aperture antenna developed by the technical staff at the Communication Research Laboratory, McMaster University, was used to collect data at various frequencies ranging from 8.05 to 12.34 GHz.

The wide-band Lake Huron data provide an ideal basis for a comparative experimental investigation of array signal-processing techniques applied to low-angle tracking. We have carried out a comparative study of performance of three approaches for tracking low-altitude targets: (1) the RML algorithm where each antenna element is treated separately; (2) the Refined MONOpulse, or RMONO, using the same specular propagation model as RML but with the upper 16 elements summed to give one output and the lower 16 summed to give the second output to form a two-element antenna array similar to a phase monopulse; and (3) phase monopulse which uses the combined outputs of the two-element array but without the specular multipath propagation model.

The report is organized as follows: section 2 presents a description of the Lake Huron trials; section 3 describes the calibration and correction of the data; section 4 contains the results of comparison between RML, RMONO and phase monopulse; and section 5 presents the conclusions and recommendations.

2. THE LAKE HURON TRIALS

2.1 The MARS System

The measurement system used in the Lake Huron experiments has been referred to as a multi-parameter array radar system (MARS) [1]. MARS comprises a remote transmitter which transmits a cw beacon signal acting as a target simulator, a 32-element sampled aperture antenna, and a data acquisition system.

In the beacon transmitter, a microwave source is phase locked to a highly stable crystal oscillator. The signal is then modulated by a carrier with the required transmitting frequency. The travelling wave tube amplifier (TWTA) is used to amplify the modulated output. The output signal from the TWTA is fed into 22-dB horns mounted on the carriage of the transmitting tower through a coaxial cable. The carriage can travel up and down to any elevation within the 16-meter vertical range (Fig. 1).

The sampled aperture antenna comprises a linear array of thirty-two 10-dB horns and associated receiver circuitry. The uniformly spaced horns form a 1.82 meter aperture. The individual array elements have been precisely aligned and are uniformly distributed to an accuracy of 0.0001 meters. Each horn is connected to a coherent receiver which has two frequency channels: a fixed-frequency channel and an agile-frequency channel. Since these two channels are identical, Fig. 2 only shows one of the channels.

The RF and IF local oscillators and the RF testing signal generator are shared by all the receivers. In the receivers, transmission line lengths and component characteristics have been carefully matched. The test channel insertion couplers, the RF mixers and the IF amplifiers are connected immediately behind each element within the antenna enclosure mounted at the top of the receiver tower. The rest of the system was installed in the equipment tent at the base of the tower. An RF signal, passing via the antenna or the test channel insertion coupler, is mixed with the RF local oscillator to obtain a 45 MHz IF signal which is amplified by the IF amplifier. The output of the IF amplifier for each receiver is mixed with the IF local oscillator in the I and Q channels to produce a baseband signal. The phase of the IF local oscillator for the Q channel is advanced by $\pi/2$. The baseband signal is amplified and low-pass filtered to obtain the field aperture distribution

which is recorded by the data acquisition system.

The data acquisition system comprises sample and hold devices, multiplexers, A/D converters, a direct memory access (DMA) controller, and a random access memory (RAM), as shown in Fig. 2. After being low-pass filtered, the baseband signals feed into the sample-and-hold circuits; the sampling rate is controllable with a maximum value of 2 KHz. The sampled signals from the 32 channels are multiplexed and then digitized by the A/D converters with 12-bit precision. The digitized outputs pass through the DMA controller via the computer bus to the RAM. At the end of each trial, the contents of the RAM are transferred to floppy disks and magnetic tape to make room in the RAM for the next run. The features of the system are summarized in Table 1.

32 10-dB H-polarized horns
1.82 meter linear aperture
0.05715 meter uniform inter-element spacing
machined ± 0.1 mm tolerance
coherent modulation
antenna elevation beamwidth of 1° (at mid-band, 10.2 GHz)
0.1 Hz Doppler resolution
1 Hz to 2 KHz sampling rate
12 bit precision

Table 1
ARRAY SPECIFICATIONS

2.2 The Measurements

The transmitter (beacon) was located at Eagle Point; the remainder of the system was installed at Warner Point, 4610 meters northwest of the transmitter site. High sea states are frequently encountered at this site because of westerly winds, the shallow water offshore, and the long fetch; the frequent occurence of high sea-state conditions was an important factor in the choice of this site. The maximum water depth along the path is 6.5 fathoms or 12 meters.

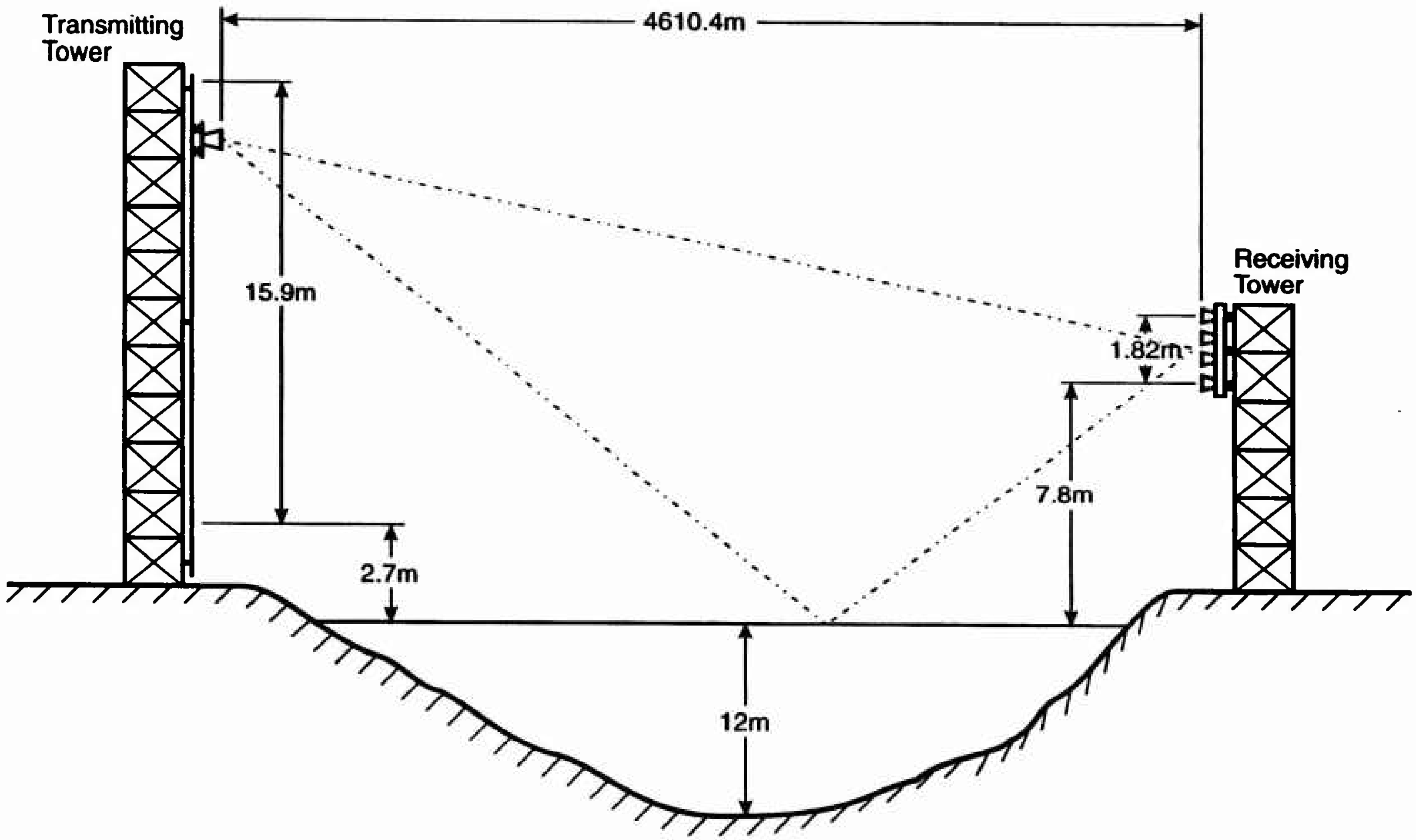

Figure 1. The measurement setup of the Lake Huron trials.

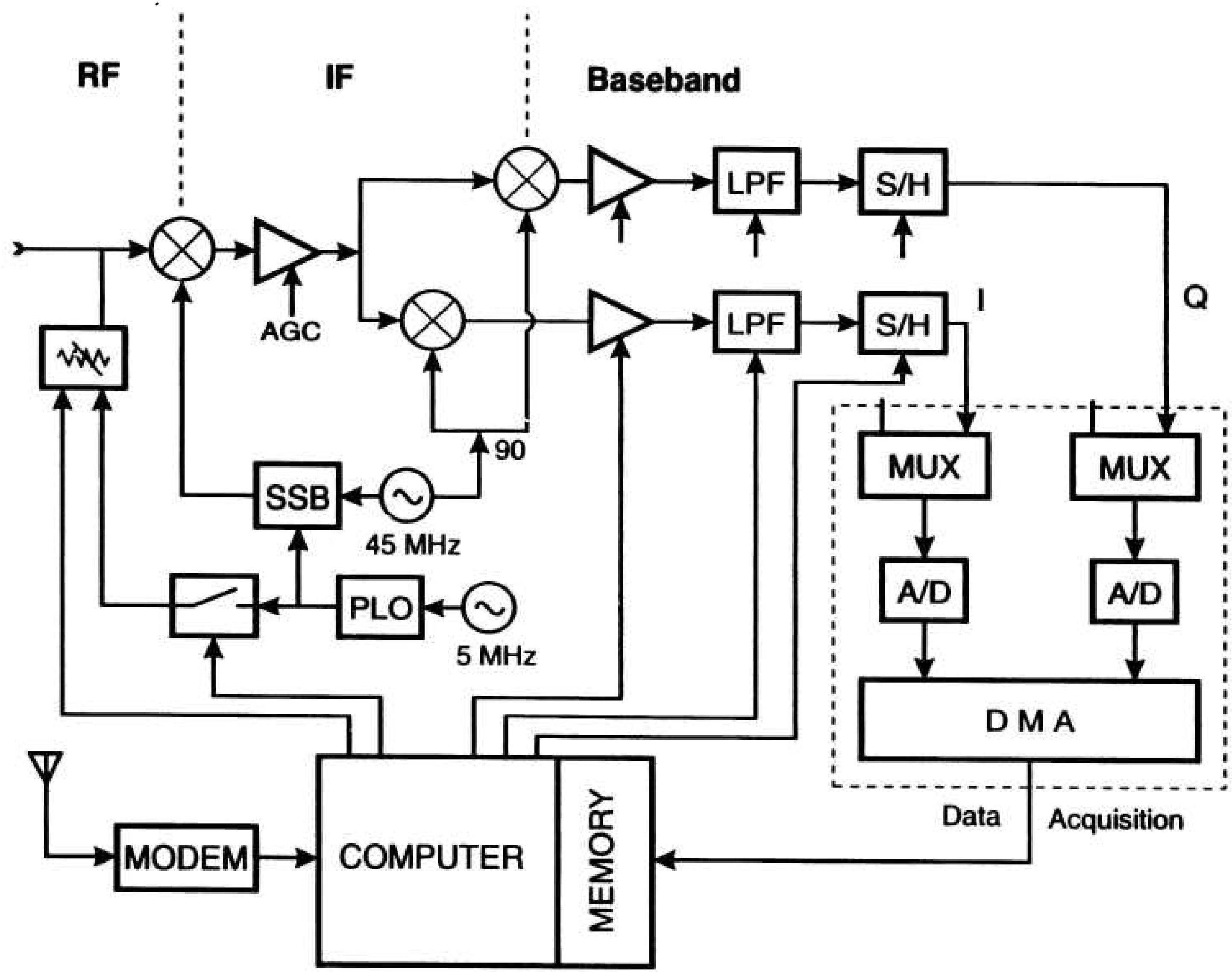

Figure 2. The receiver system, showing only one channel.

Two frequencies are simultaneously used for transmission. The fixed channel has a frequency of 10.2 GHz. In principle, 145 possible frequencies are available for measurement. However, only 17 frequencies were used in the trials as listed in Table 2.

Agile-frequency channel:

8.05 GHz	8.32 GHz	8.62 GHz	8.92 GHz	9.22 GHz	9.52 GHz
9.82 GHz	10.12 GHz	10.42 GHz	10.72 GHz	11.02 GHz	11.32 GHz
11.62 GHz	11.92 GHz	12.22 GHz	12.34 GHz		

Fixed-frequency channel:

10.2 GHz

Table 2

Frequencies used for measurements

An electronic device, intended to accurately measure the sea roughness, malfunctioned during the trials. Therefore the sea surface conditions were estimated from visual observation. Meteorological information was obtained from a mini weather station. Observations were made each hour during the trials. The day-average information is given in Table 3.

Date	Wind Speed (km/hr)	Wind Direction	Pressure (mbars)	Temp. (^oC)	Wave height (meters)
Oct 31	2	E	973	7	0.3
Nov 1	5	E	974	10	0.3
Nov 2	7	SW	964	10	0.5
Nov 3	8	SW	954	12	1.0
Nov 4	18	WSW	944	12	1.5

Table 3

Meteorological Information

About 40 Mbytes of multipath data were collected during the 5-day trial period. As shown in Table 3, different meteorological conditions were encountered during each of the five days. Table 4 gives the environmental conditions for the period of Nov. 1-4. Each trial lasted for one or two seconds followed by the next trial with a different set of experimental parameters. The data were collected in discrete short bursts of 64 or 127 samples. Since the sampling rate used in the measurement was 62.5 samples/second the time duration of a data set was 1.024 seconds for 64 samples or 2.032 seconds for 127 samples. The starting time of each data set was recorded.

(a) Nov. 1, 1987

Time	Wind km/hr (max)	Wind km/hr (avg)	Wind dir	Press (mbar)	Temp (oC)	Observations
10:00	10	3	SE	972	9	It is very calm throughout the day. Only ripples on the surface are observed Fishing boat 16E261 is active near the propagation path from 11:00 to 12:00. It is sunny during the day.
11:00	18	4	E	973	9	
12:00	18	6	E	974	13	
13:00	17	6	E	974	13	
14:00	19	7	E	974	12	
15:00	19	4	E	975	12	
16:00	19	2	E	975	10	
17:00	19	3	ESE	973	7	
18:00	4	1	NNE	972	4	
19:00	7	3	E	972	4	

(b) Nov. 2, 1987

Time	Wind km/hr (max)	Wind km/hr (avg)	Wind dir	Press (mbar)	Temp (oC)	Observations
09:39	13	7	SSW	965	9	It is cloudy in the morning. 0.5-m waves on the water surface are observed. It begins to rain at 12:45.
11:00	22	6	WSW	966	10	
12:00	12	8	SW	966	10	
13:30	16	6	SSW	964	10	
14:15	10	7	SSW	963	10	
15:30	14	5	WNW	963	10	

Table 4
Environmental Conditions

Table 4 (continued)

(c) Nov. 3, 1987

Time	Wind km/hr (max)	Wind km/hr (avg)	Wind dir	Press (mbar)	Temp (oC)	Observations
08:53	18	14	WNW	952	11	Raining heavily in the A.M. 1-m waves on the water observed. Stops Rain at 11:00. Sun comes out briefly at 14:00. Then cloudy again. Thunder storm at 20:26 and trials stop.
09:51	19	12	W	954	11	
12:00	21	8	WSW	954	12	
13:00	21	8	WSW	954	12	
14:00	14	3	SW	954	14	
15:00	14	3	SW	953	13	
16:00	14	3	SW	952	12	
17:00	15	6	S	950	11	
18:00	19	8	SW	949	12	
19:00	21	11	SW	949	12	
20:00	25	11	S	948	11	
20:26	25	11	S	947	11	

(d) Nov. 4, 1987

Time	Wind km/hr (max)	Wind km/hr (avg)	Wind dir	Press (mbar)	Temp (oC)	Observations
09:00	21	15	WSW	942	12	Partially cloudy in the A.M 1.5-m waves are observed. At 11:00 it starts to rain. Rain stops at 13:00.
10:00	31	20	S	944	12	
11:00	31	26	WSW	944	12	
13:00	35	16	W	944	12	
14:00	25	15	WNW	944	11	

2.3 Data Format

A data file contains a number of data sets from trials with different measurement parameters. All the data sets have the format illustrated in Fig. 3. The preamble to a data set contains a number of important system and measurement parameters including the starting time at which a set of data was recorded. Table 5 lists the parameters relevant to the measured data. Data are stored in blocks designated as snapshots, each snapshot comprising the digitized I and Q outputs from each of 32 elements for the fixed and agile frequencies (128 16-bit words). The total number of words in a data set are Nx128 where N is the number of samples. Detailed information about the data files is given in Appendix A.

CAR AT *p*	Elevation of the horn carriage = p + 186.374 m gives the 'Home' position of the carriage above sea level. Lake elevation is 176.80 m.
# of Data Samples	# of Snapshots
System Freq Step	Each step = 30.0 MHz
VCO Freq Offset	δf (Hz), frequency offset of the voltage controlled oscillators of the transmitter and receiver (see IQ Calibration)
Test Tone	1=on, 0=off (see IQ Calibration)
Test Atten	Test signal attenuation (dB)
Xmtr Freq Step	This should agree with the system frequency step

Table 5
Measurement parameters in the preambles

Preambles	64 lines of 64 characters
Tilt-meter readings-Erroneous (N 16-bit integer words)	word 1
	word 2
	......
	word N
Array data (16 bit integer words) Snap 1, Element 1, Fix Freq, Ch I	word 1
Snap 1, Element 1, Fix Freq, Ch Q	word 2
Snap 1, Element 1, Agile Freq, Ch I	word 3
Snap 1, Element 1, Agile Freq, Ch Q	word 4
......	......
Snap 1, Element 32	word 128
Snap 2, Element 1	word 129
....	......
Snap 2, Element 32	word 256
......	......
Snap N, Element 1	word 128(N-1)+1
......	......
Snap N, Element 32	word 128 N

(Snap=snapshot=data vector)

Fig. 3 The format of a data set.

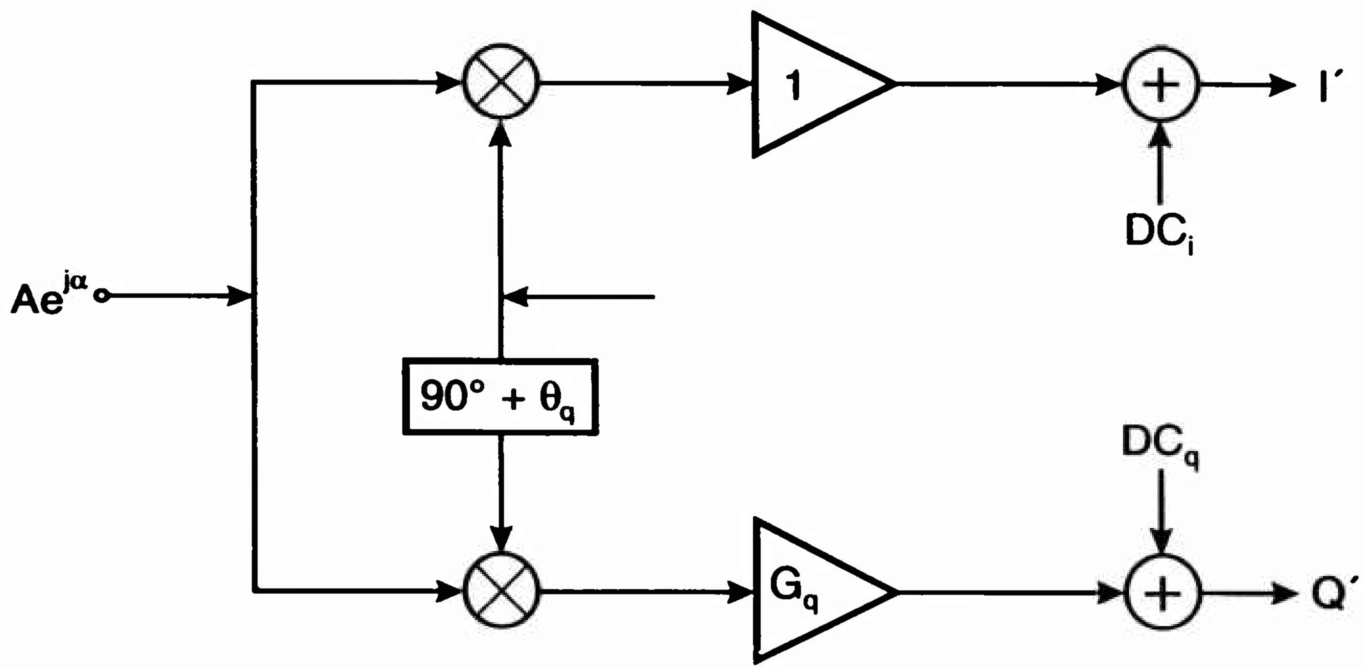

Figure 4. Channel model for IQ calibration.

3. CORRECTION and CALIBRATION OF THE DATA

The collected data must be calibrated for errors resulting from (dc) offsets in the I and Q channels and differences in the gain and phase characteristics of individual receivers. Two procedures were used: IQ correction and far field calibration.

3.1 IQ Correction

This procedure is designed to measure the gain and phase characteristics of the individual channels of the IF and the baseband stages using the channel model depicted in Fig. 4. The gains in both channel I and channel Q are normalized with respect to that of channel I. Therefore, the gain in channel I is unity and the gain in channel Q is G_q. Θ_q represents the relative phase error in channel Q. The dc offsets in both channels are DC_i and DC_q. If the input is an IF signal of the form $Ae^{j\alpha}$, the outputs of both channels are expected to be

$$I = A\cos(\alpha) \tag{1}$$

and

$$Q = A\sin(\alpha) \tag{2}$$

Because of the gain and phase errors and the dc offsets in the channels, the actual outputs are

$$I' = A\cos(\alpha) + DC_i \tag{3}$$

and

$$Q' = A\,G_q \sin(\alpha - \Theta_q) + DC_q \tag{4}$$

Solving for $\cos(\alpha)$ and $\sin(\alpha)$ in Eqs. (3) and (4) and substituting them into Eqs. (1) and (2), we obtain the true in-phase and quadrature-phase components of the signal,

$$I = I' - DC_i \tag{5}$$

and

$$Q = \frac{1}{\cos(\Theta_q)}\left[\frac{Q' - DC_q}{G_q} + I\sin(\Theta_q)\right] \quad (6)$$

The parameters DC_i, DC_q, G_q and Θ_q, referred to as IQ calibration coefficients, are determined for each of the receivers.

DC_i and DC_q can be easily determined as follows:

$$DC_i = \frac{1}{N}\sum_{n=1}^{N} I'(n) \quad (7)$$

$$DC_q = \frac{1}{N}\sum_{n=1}^{N} Q'(n) \quad (8)$$

where N is the number of samples and I' and Q' are the channel data in file CIQ*.DAT

G_q and Θ_q can be measured by injecting a test signal whose frequency is offset from the receiver IF frequency by a small amount δf Hz. Any imbalance in gain and phase will create an image response at $-\delta f$ and hence G_q and Θ_q can be found as follows. Let

$$S'(n) = I'(n) + j\,Q'(n) \quad (9)$$

where

$$I'(n) = A\cos(2\pi\delta f\, nT) + DC_i \quad (9a)$$

$$Q'(n) = A\,G_q\sin(2\pi\delta f\, nT - \Theta_q) + DC_q \quad (9b)$$

The Discrete Fourier Transform (DFT) of S' evaluated at δf is given as

$$F\{S'\}_{\omega=2\pi\delta f} = \sum_{n=0}^{N-1} S'(n)\, e^{j\omega nT} = \frac{NA}{2}\left(1 + G_q\cos(\Theta_q) - jG_q\sin(\Theta_q)\right) \quad (10)$$

where F{_} denotes the DFT.

Similarly, the DFT of S' evaluated at $-\delta f$ is

$$F\{S'\}_{\omega=-2\pi\delta f} = \sum_{n=0}^{N-1} S'(n)\, e^{-j\omega nT} = \frac{NA}{2}\left(1 - G_q\cos(\Theta_q) - jG_q\sin(\Theta_q)\right) \tag{11}$$

Solving Eqs. (10) and (11) gives the parameters G_q and Θ_q of a channel. By repeating the procedures for all 32 elements, a set of calibration coefficients can be obtained and the measured data can be corrected with Eqs. (5) and (6).

3.2 Far Field Calibration

Calibration with a far-field source is required to calibrate for insertion phase and gain errors of the signal distribution network. The previously described IQ calibration serves only to insure that the IQ channels are orthogonal. Indeed, the IQ calibration may introduce insertion phase errors since the network that distributes the test signal is different from the signal distribution network. The technique uses a far field source to provide uniform illumination across the aperture as a basis for evaluating the relative parameters.

A 22-dB horn was connected to the transmitter and placed less than a foot above the water surface. The geometry of the far-field calibration setup is given in Fig. 5. Although multipath existed, we modeled the return as a single plane wave because the separation between the source and the image was so small as to be negligible. From the knowledge of the geometry, aperture distribution data were simulated and compared with the outputs of the receivers to obtain a set of calibration coefficients. The far-field calibration coefficients $A_{ff}e^{j\varphi_{ff}}$ are the average corrections that must be applied to the measured data $A_m e^{j\varphi_m}$ from a CFF*.DAT file such that they agree with the simulated data $A_s e^{j\varphi_s}$, i.e.

$$A_{ff}e^{j\varphi_{ff}} = \frac{1}{N}\sum_{n=1}^{N} \frac{A_m(n)e^{j\varphi_m(n)}}{A_s(n)e^{j\varphi_s(n)}} \tag{12}$$

It should be pointed out that this approach is based on the assumption that a single plane wave impinges on the array. With the calibration coefficients, the measured multipath data at the output of a receiver, $Ae^{j\varphi}$ can be corrected as follows

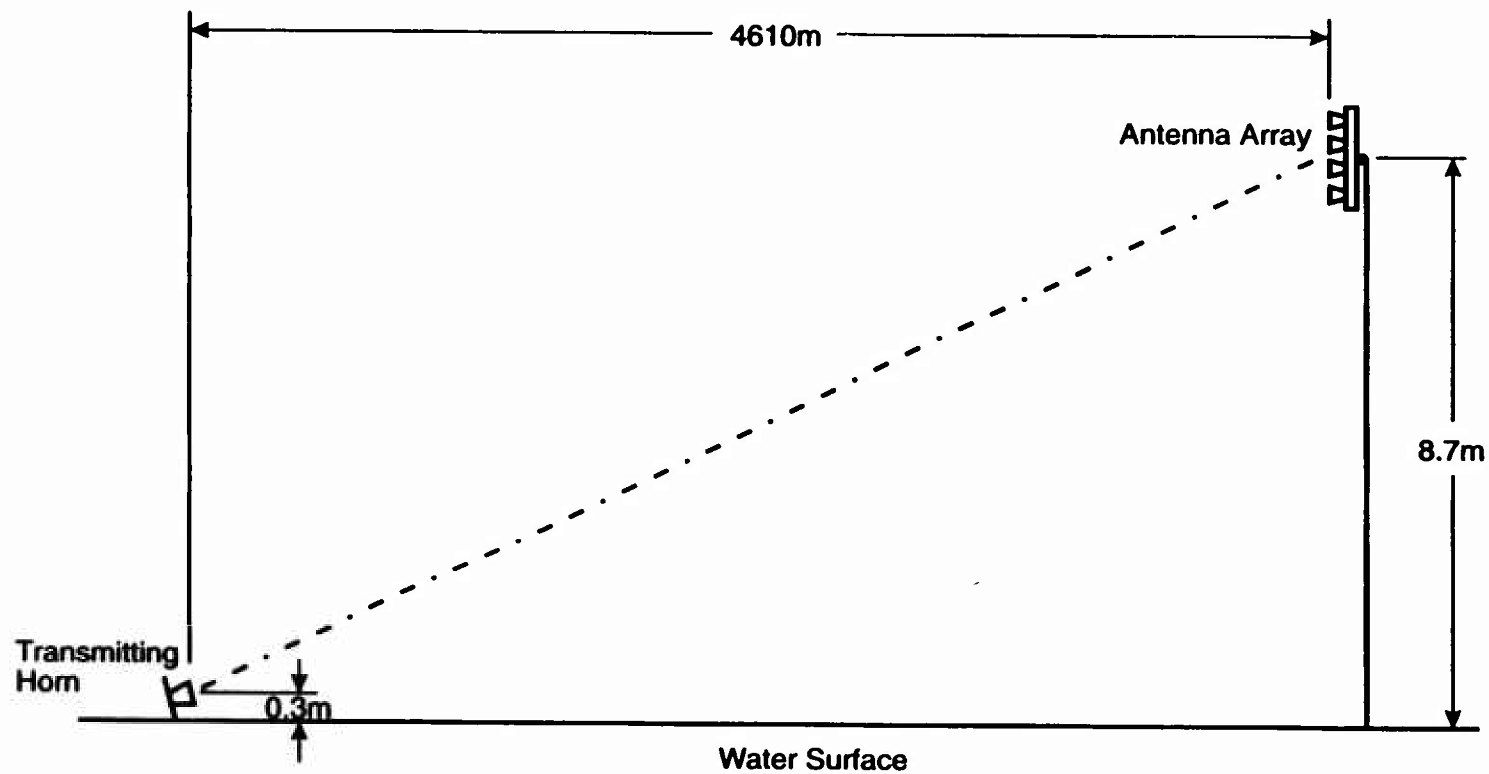

Figure 5. The geometry of the far-field calibration setup.

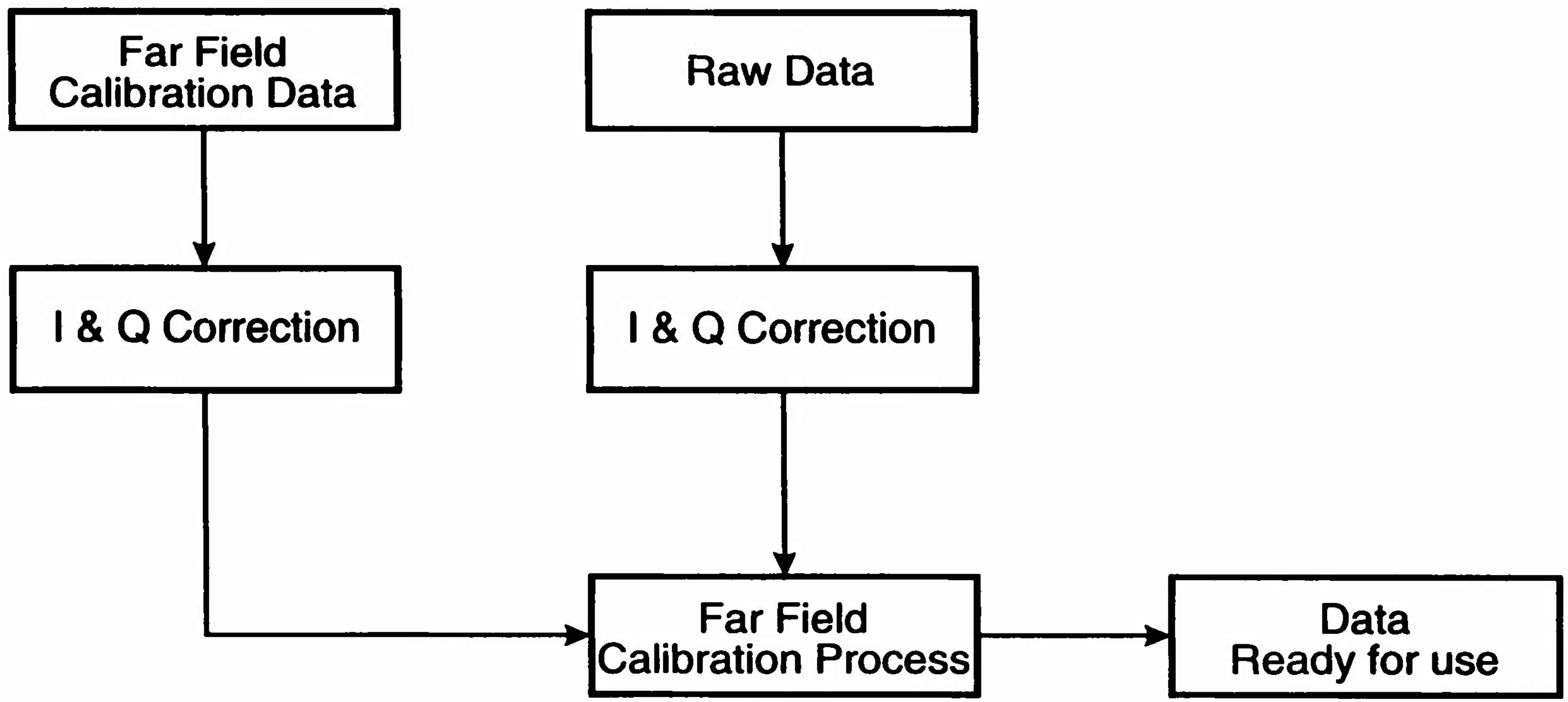

Figure 6. Functional block diagram of the calibration and correction process.

$$A_c e^{j\varphi_c} = \frac{A e^{j\varphi}}{A_{ff} e^{j\varphi_{ff}}} \tag{13}$$

where the subscript c implies the corrected values. After the IQ calibration and the far-field calibration are completed, the experimental data are ready to be analyzed. Fig.6 shows a functional block diagram of the calibration and correction process. Appendix A gives the details for creating calibration tables.

4. THE RMONO AND RML ALGORITHMS

The distinction between the RML and RMONO algorithms is that the RML algorithm is applied to a general N-element array while RMONO is a specialized version of RML where we are restricted to two outputs corresponding to the two halves of a large antenna. The application of RML to a two-element array gives RMONO.

The RML algorithm has been described extensively in the following references [2-3]. Therefore, we present here only a brief summary. In the present development of the RML algorithm, we use the method described by Kerr [6] to represent the interaction between the direct and the indirect signals as seen by a vertical array antenna. Here, we assume a medium that is linear, homogeneous, isotropic, and frequency invariant (narrowband). The influence of the atmosphere on the radar propagation is accounted for by using an equivalent earth radius. The model requires knowledge of the target range (initially obtained from an acquisition radar and then maintained as part of the track update process), the reflection coefficient (amplitude and phase), and the specular scattering coefficient (function of sea state). The signal variation over a vertical array is written as

$$\mathbf{s}_m = b_m \mathbf{f}_m(h) + \eta_m \tag{1}$$

Here $\mathbf{f}_m$ is the model vector, h is the target height, b_m is an unknown complex constant and η_m is the vector of complex receiver noise over the array. The subscript m indicates the frequency in the case of frequency agility and the vectors $(\mathbf{s}_m, \mathbf{f}_m, \eta_m) \in C^{K\times 1}$, $b_m \in C^{1\times 1}$ and where b_m can be deterministic (non-fluctuating case) or random (fluctuating case). The noise vector η_m is assumed to be stationary, additive, spatially white and independent of the target signals. The quantity K represents the number of sensors. The vector s is called a snapshot of the antenna array outputs. In the case of

RMONO, the vectors **s** and **f** have only two elements. Phase monopulse is implemented by using (14) and setting the reflection coefficient equal to zero in $\mathbf{f}_m(h)$.

The RML algorithm uses prior knowledge of the radar height above the sea, the target range, and sea state in a "refined" propagation model having a small number of unknowns: target height and an amplitude and phase for each radar frequency. A maximum likelihood estimator for target height is obtained by fitting this model to the observed array in a least-squares sense. The unknown amplitude and phase associated with each frequency can be eliminated mathematically leaving a likelihood function having one unknown: the target height. The RML algorithm is given by the following equation:

$$\mathrm{RML}(h) = \frac{1}{\sum_{m=1}^{M} \frac{|\mathbf{s}_m|^2}{\sigma_m^2}} \sum_{m=1}^{M} \frac{|\mathbf{s}_m^H \mathbf{f}_m(h)|^2}{\sigma_m^2 |\mathbf{f}_m(h)|^2} \tag{14}$$

By using the Cauchy-Schwartz inequality, we can show that $0 \leq \mathrm{RML}(h) \leq 1$.

5. EVALUATION OF TRACKING PERFORMANCE

This section illustrates the use of the data base for evaluating three low-angle tracking techniques: refined maximum likelihood (RML), refined monopulse (RMONO) and phase monopulse. The RML algorithm in this comparison is applied to all 32 elements of the receiving array. The RMONO algorithm is implemented by applying the RML algorithm to only two subarrays, one subarray comprising the sum of the upper sixteen elements, the other comprising the sum of the lower sixteen elements. Phase monopulse is implemented by estimating the target elevation angle as a function of the phase difference between the outputs of the two subarrays assuming a single incident plane wave.

The evaluation of relative performance has been carried out using two data files for which good calibration information was available. The data in file DH4.NV3 is labelled example #1, that in data file DH3.NV3 is labelled example #2. For these results the beacon transmitter antenna was at approximately eighteen metres above the water. Repeated application of the estimation algorithms for RML, RMONO and phase monopulse are plotted as functions of the estimate number with each estimate made on the basis of m data snapshots, where m is the number of agile frequencies. The results are presented in Figs.7-14, so as to illustrate the relative performance of the three techniques as a function

of the agile bandwidth of the data and the number of agile frequencies within the bandwidth: bandwidths of 2 and 4 GHz having 3 and 5 frequencies distributed over the bandwidth have been selected. The corresponding RMSEs have been calculated and are presented in Table 6. Table 6 presents also the RMSE improvements with respect to phase monopulse performance.

The results of Figures 7-14 and Table 6 lead to the following observations:

1. For most of the Lake Huron data, RML and RMONO gave nearly the same tracking performance. That RMONO performed so well in comparison to RML is attributed to the very good calibration and the high signal-to-noise ratio for the data. Other results [6] indicate that RML is much more robust than is RMONO when significant calibration errors are present and/or the signal-to-noise ratio is reduced.

2. The performance of RML and RMONO is very much dependent upon the bandwidth and number of frequencies employed. For a 2 GHz bandwidth, significant errors were observed with both 3 frequencies and 5 frequencies; these errors were typical of ambiguities caused by erroneously selecting local maxima of the likelihood function. For these cases, the RMSEs of phase monopulse were 1-2 times larger than with RMONO or RML. The real advantages of RMONO were only observed when using an adequate degree of frequency agility (5 frequencies) over a sufficiently large bandwidth (4 GHz). In this case, RMONO and RML have RMSEs approximately 60 times smaller than those of phase monopulse.

3. For both RMONO and RML, it is evident that the achievement of good results depends on an adequate degree of frequency agility over a sufficient large bandwidth.

6. CONCLUSION

The first part of the report documents an important and useful data base for comparative evaluation of low-angle tracking techniques. This data base has features which in combination make it unique: the very wide bandwidth (8-12 GHz), the large number of array elements (32), with very well calibrated data collected in up to sea-state 3 conditions. This documentation includes a description of the calibration procedures necessary to obtain reliable results.

The second part of the report uses the data base to compare the performance of three low-angle tracking techniques: phase monopulse applied to two 16-element subarrays of a 32-element antenna array, refined maximum likelihood applied to the same two subarray outputs (RMONO), and refined maximum likelihood estimation applied to all 32 elements of the array (RML). The latter technique, RML, is optimum for tracking in specular multipath and performed the best; however, the computational load is high and individual receivers are required for each array element. For the very well calibrated experimental data base, RMONO was shown to perform nearly as well as RML. RMONO is therefore a cost-effective solution since it requires only two receiver channels and poses a smaller computational load than RML. The advantages of RMONO can be realized, however, only if the antenna calibration is of high quality and the radar has a wide agile bandwidth.

The present trend in naval radars is towards active phased-array radars for ship defence. Such systems with their solid-state transceiver modules are able to support a very wide agile bandwidth. The use of RMONO in such a radar system could significantly improve the accuracy of target height estimation in multipath conditions.

In cases where the high precision of RMONO is not required and / or the bandwidth and antenna calibration are not sufficient to support good performance with RMONO, tracking performance may still be significantly improved by averaging monopulse estimates over a number of frequencies within the agile bandwidth.

Run 4; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 9.22, 10.12 GHz

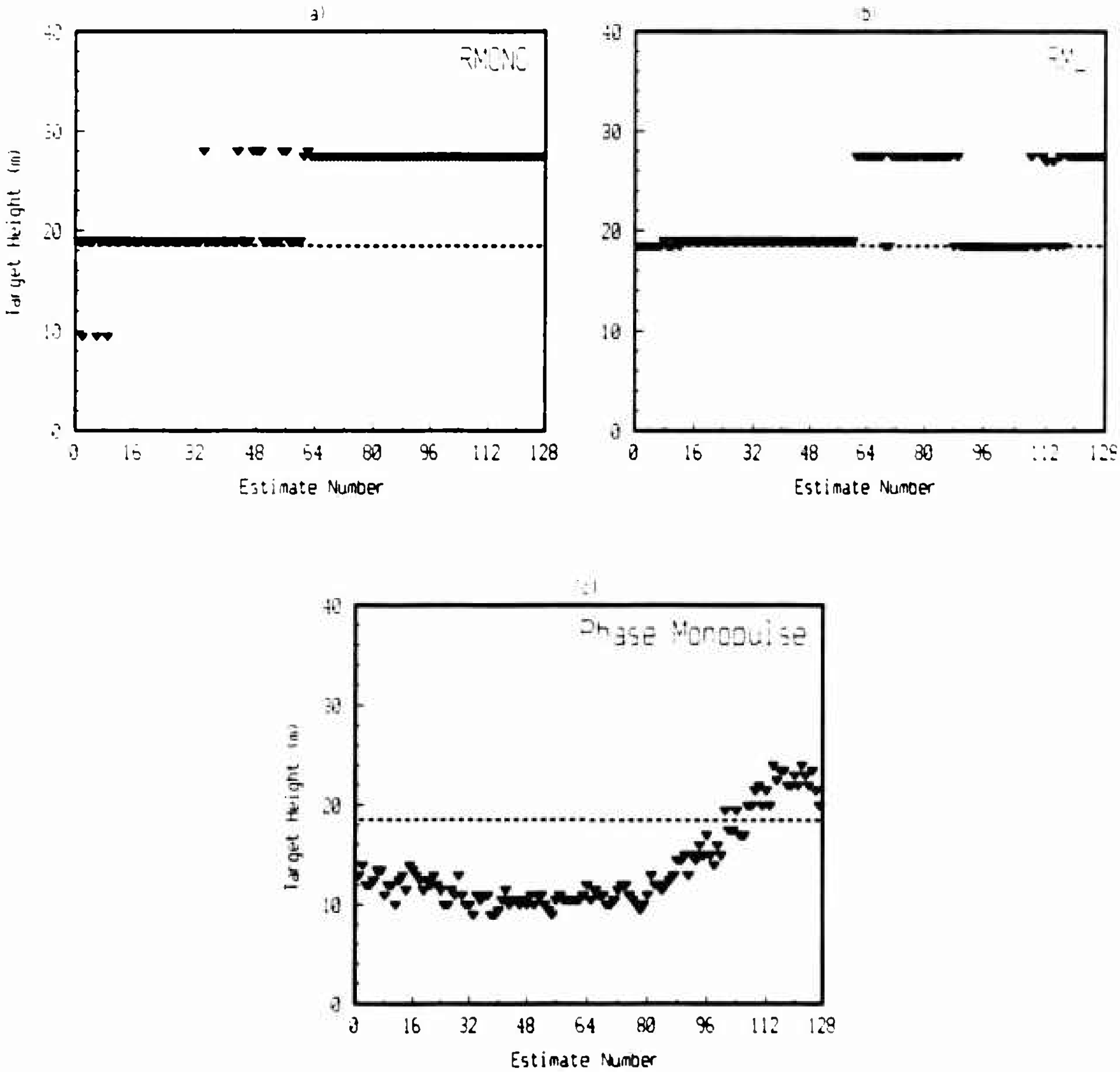

Figure 7: Tracking performance using three frequencies and a two GHz bandwidth : example 1.

Run 4; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 8.62, 9.22, 9.82, 10.12 GHz

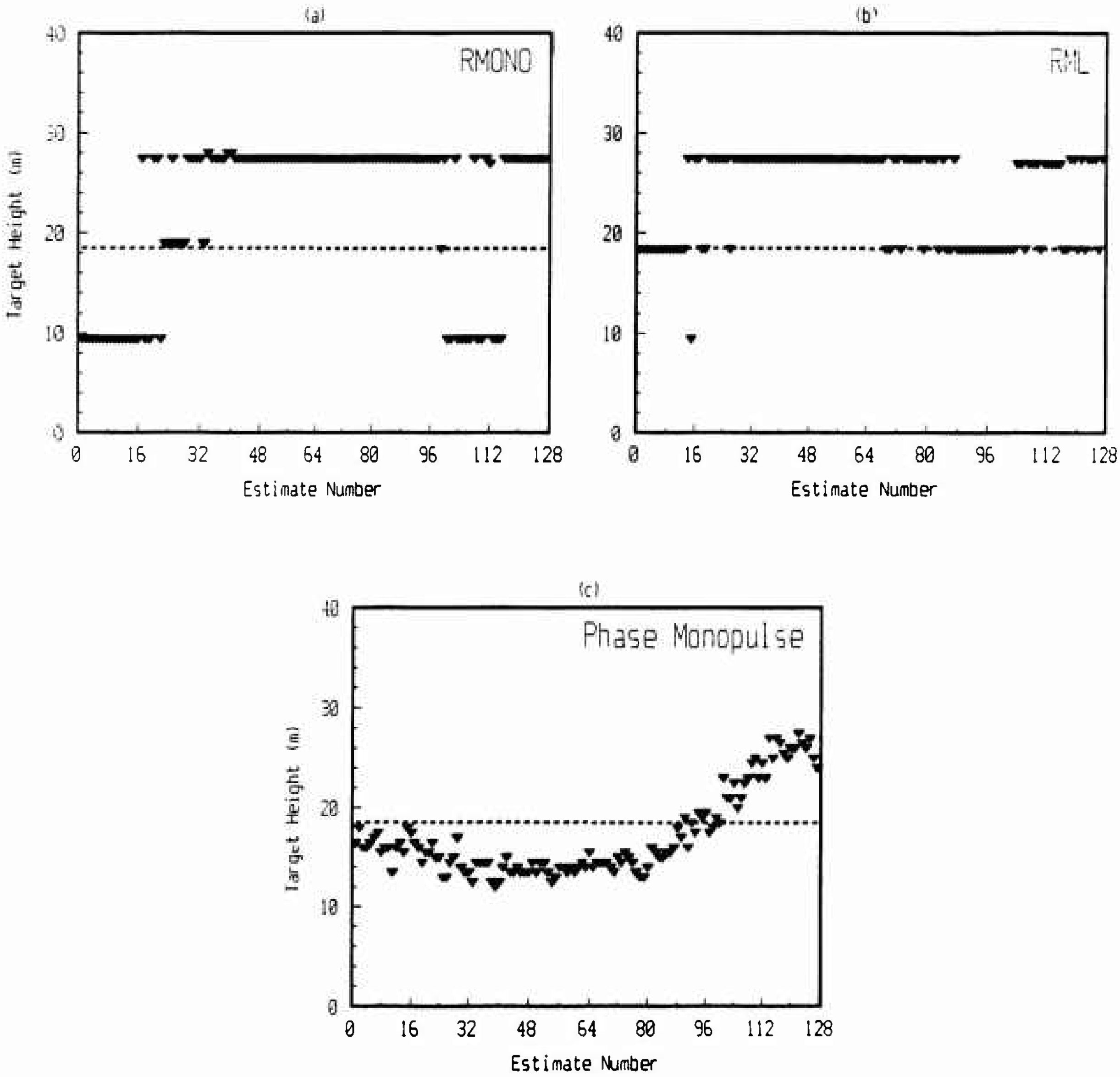

Figure 8: Tracking performance using five frequencies and a two GHz bandwidth : example 1.

Run 3; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 9.22, 10.12 GHz

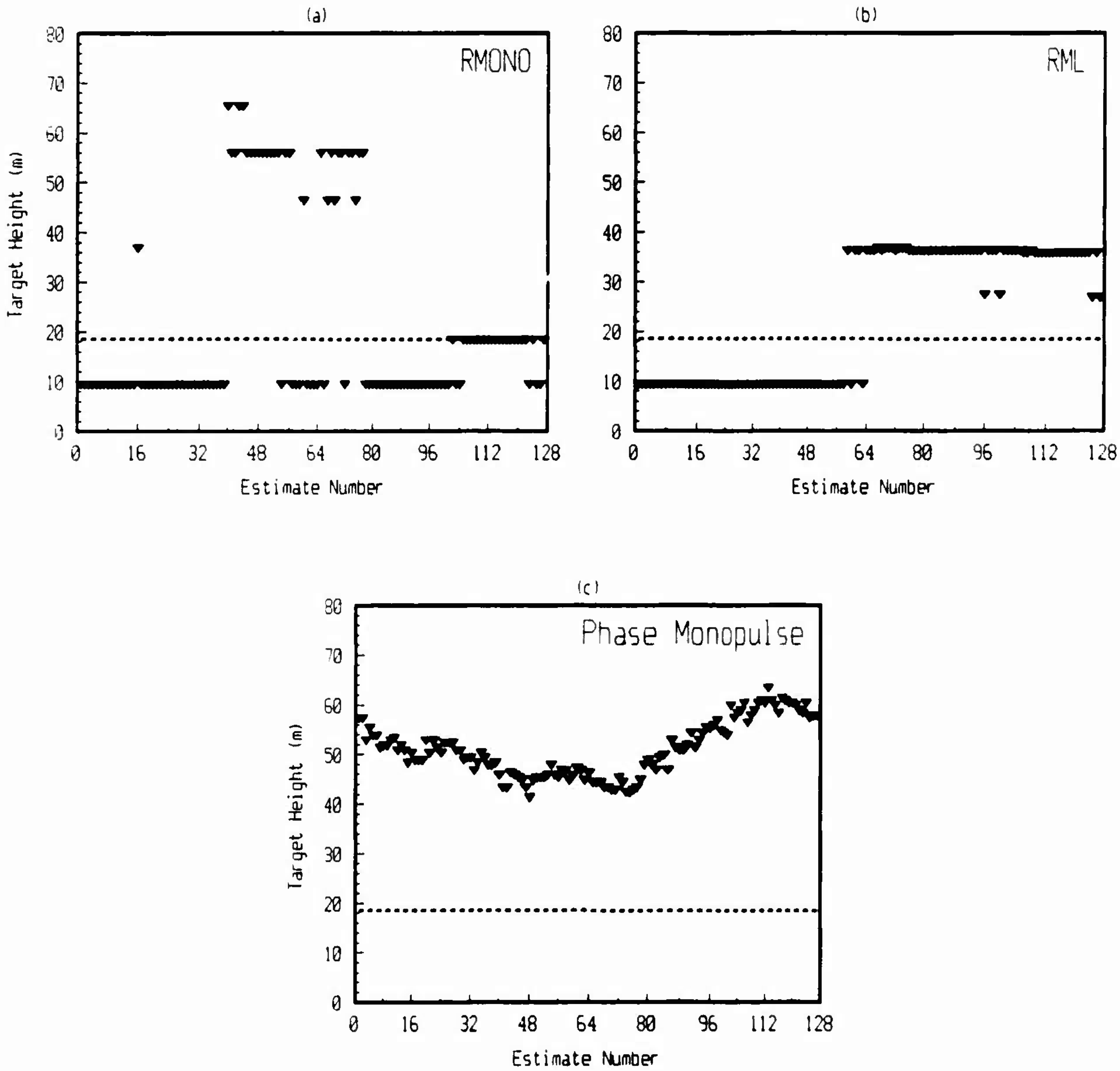

Figure 9: Tracking performance using three frequencies and a two GHz bandwidth : example 2.

Run 3; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 8.62, 9.22, 9.82, 10.12 GHz

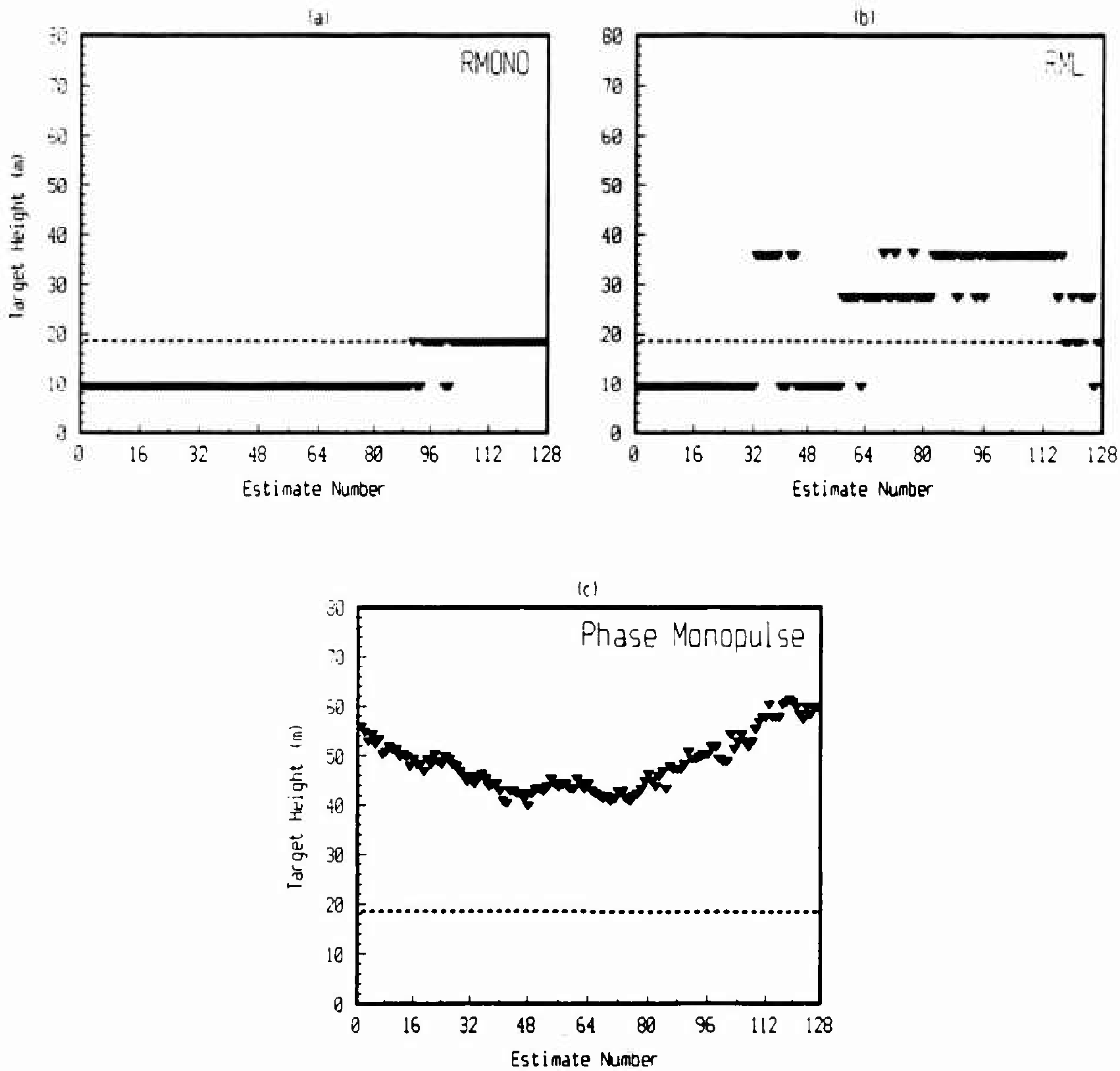

Figure 10: Tracking performance using five frequencies and a two GHz bandwidth : example 2.

Run 4; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 10.12, 12.34 GHz

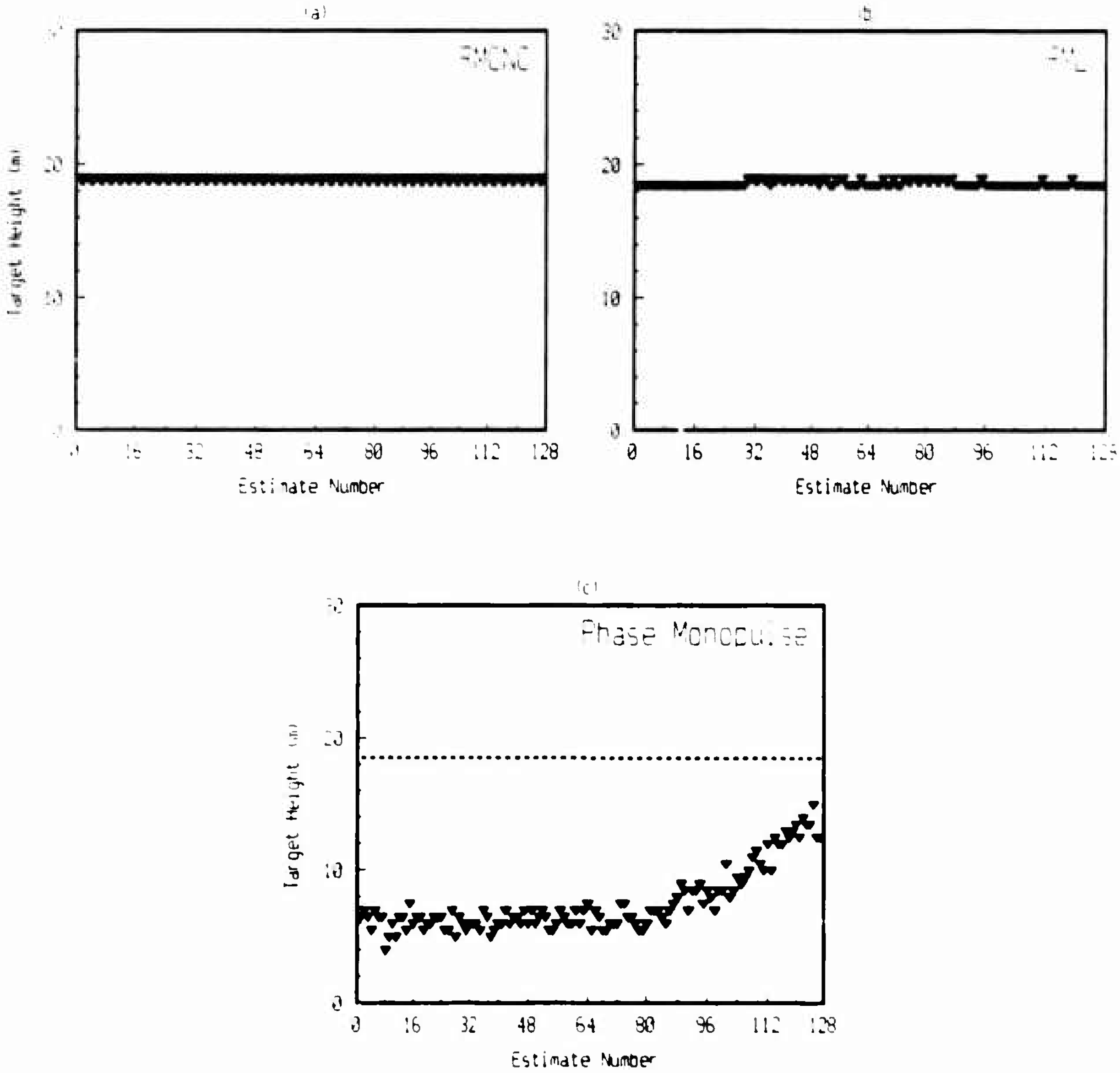

Figure 11: Tracking performance using three frequencies and a four GHz bandwidth : example 1.

Run 4; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 9.22, 10.42, 11.62, 12.34 GHz

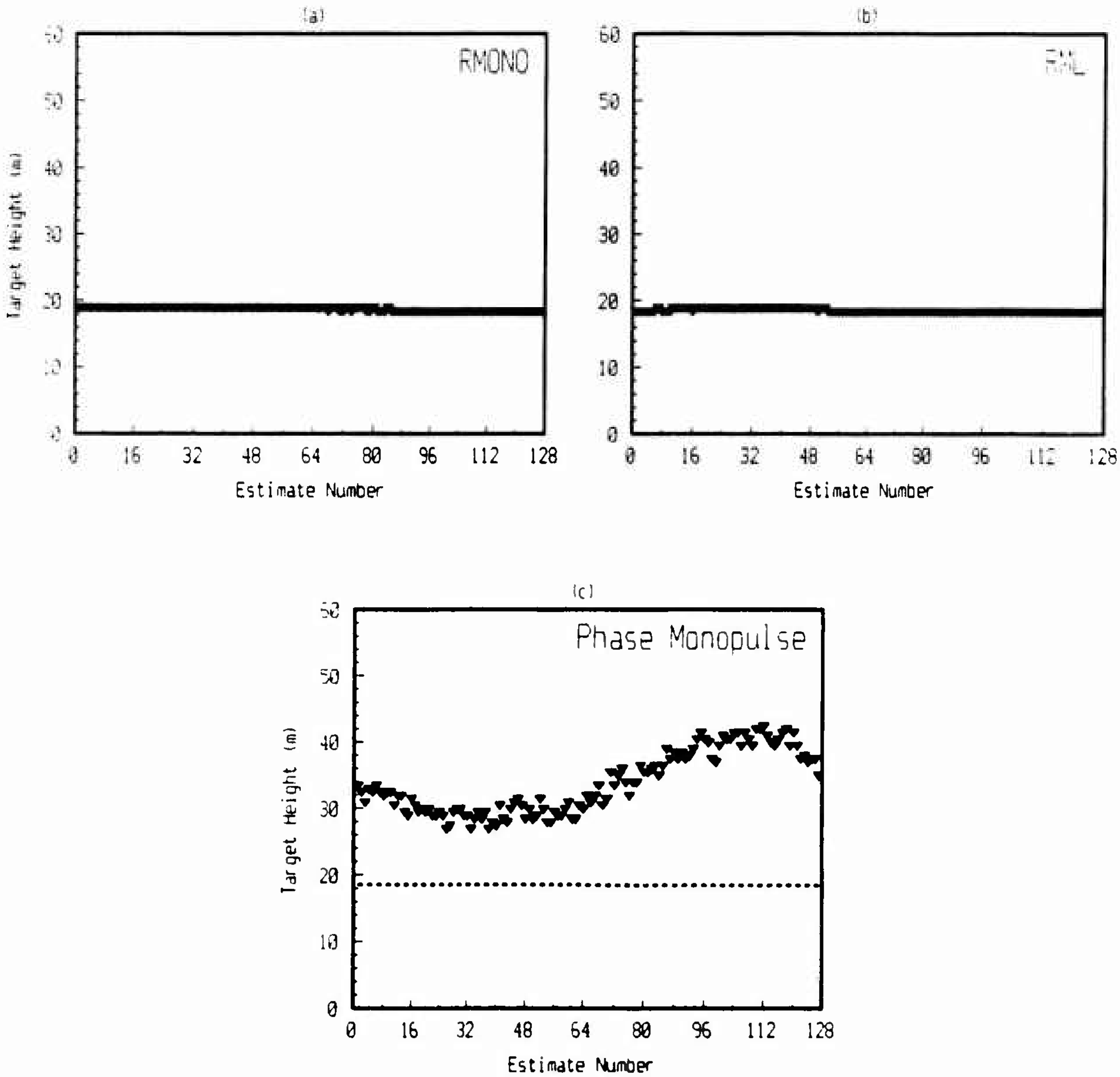

Figure 12: Tracking performance using five frequencies and a four GHz bandwidth : example 1.

Run 3; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 10.12, 12.34 GHz

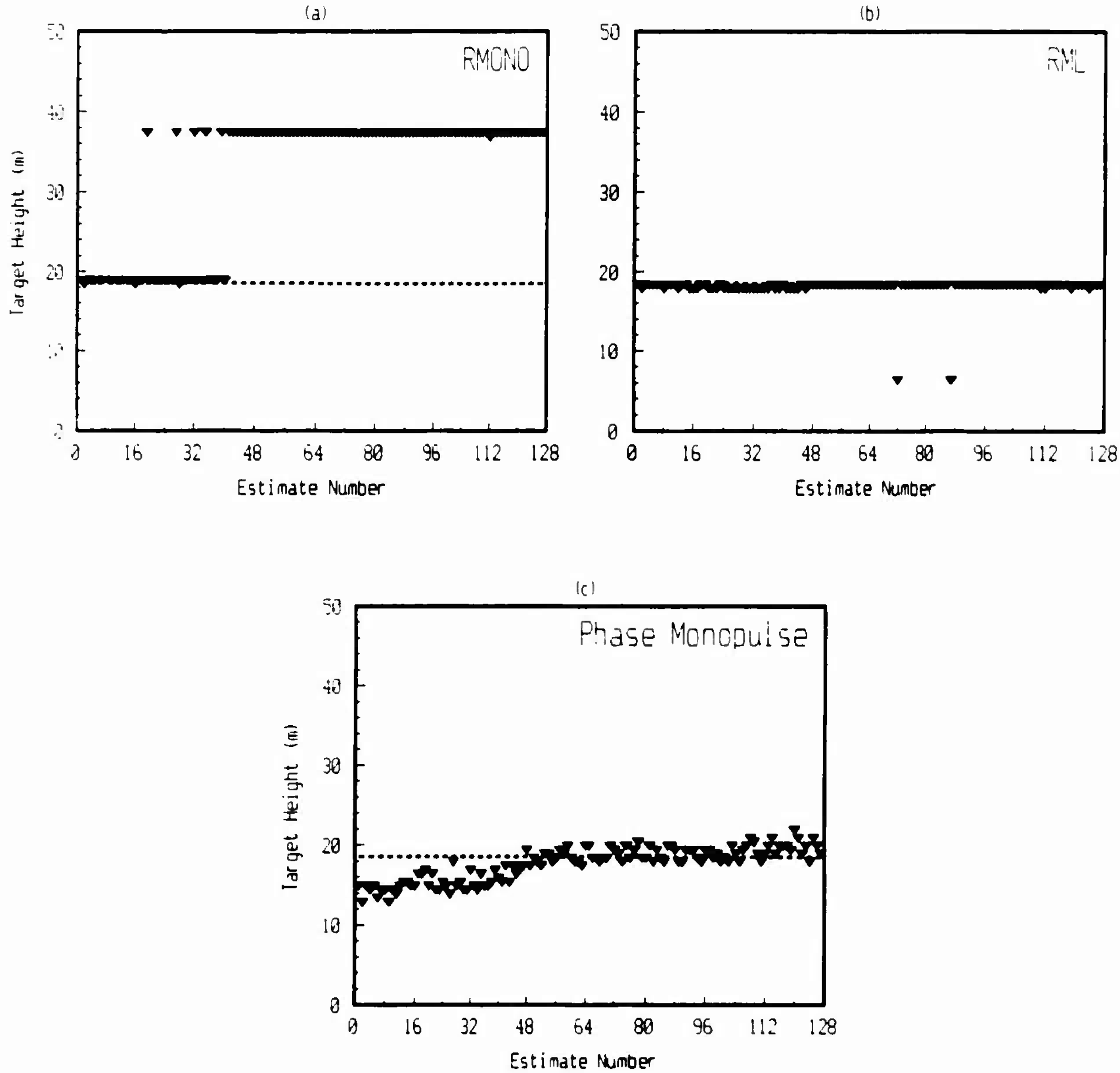

Figure 13: Tracking performance using three frequencies and a four GHz bandwidth : example 2.

Run 3; November 3, 1987; Horizontal Polarization
Frequencies: 8.05, 9.22, 10.42, 11.62, 12.34 GHz

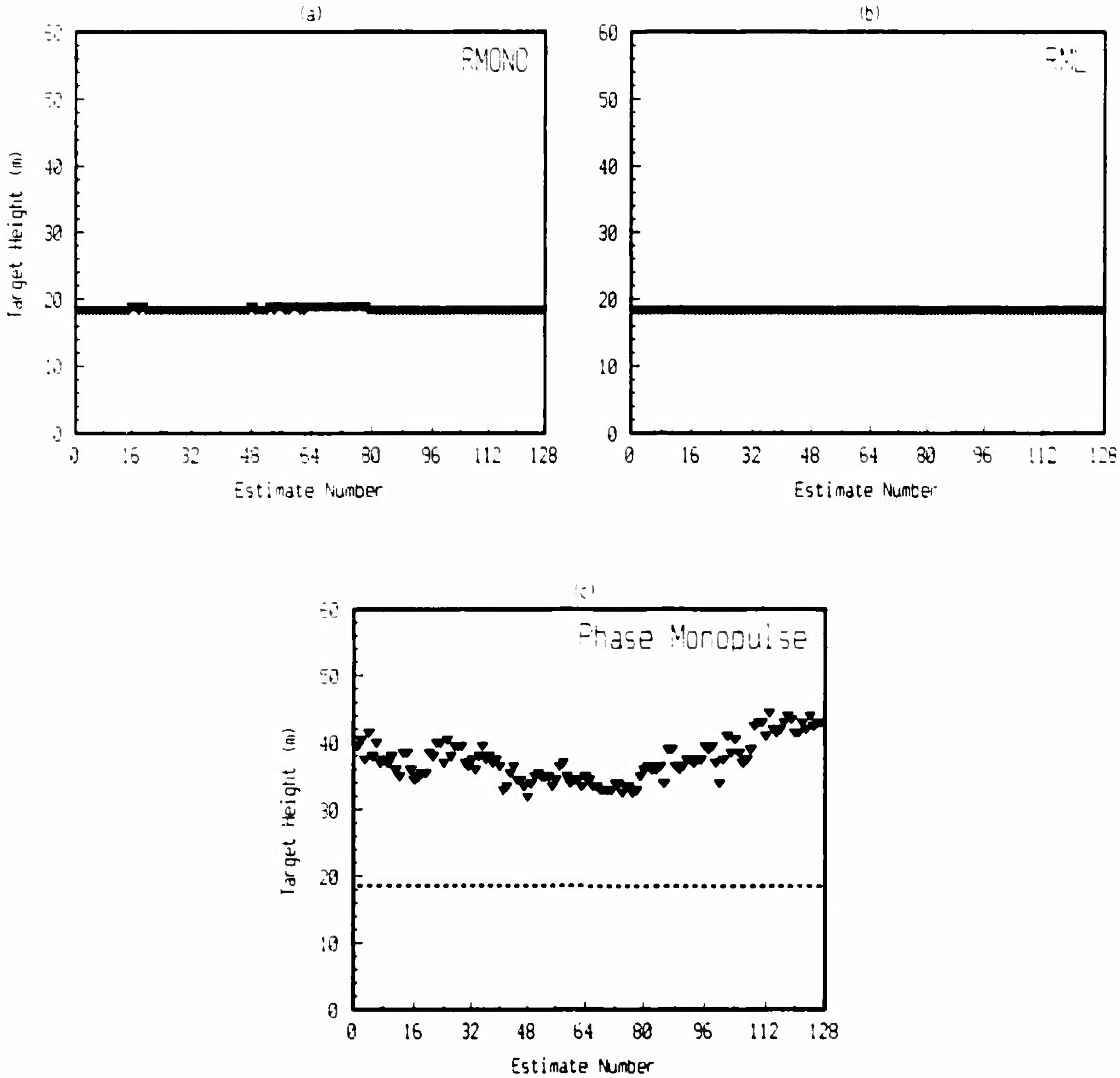

Figure 14: Tracking performance using five frequencies and a four GHz bandwidth : example 2.

Table 6:
Lake Huron Data
RMS Errors (meters)

Bandwidth: 2 GHz and 3 frequencies

Figure 7(a) RMONO	7.056298
Figure 7(b) RML	5.109818
Figure 7(c) Ph Mono	6.420930
Figure 9(a) RMONO	19.00549
Figure 9(b) RML	14.13350
Figure 9(c) Ph Mono	33.14321

RMSE IMPROVEMENT: RMONO: 1.54 RML: 2.08 Phase Mono:1.00

Bandwidth: 2 GHz and 5 frequencies

Figure 8(a) RMONO	8.757674
Figure 8(b) RML	7.139499
Figure 8(c) Ph Mono	4.423230
Figure 10(a) RMONO	7.742917
Figure 10(b) RML	12.42964
Figure 10(c) Ph Mono	30.74767

RMSE IMPROVEMENT: RMONO: 1.06 RML: 1.8 Phase Mono:1.00

Bandwidth: 4 GHz and 3 frequencies

Figure 11(a) RMONO	0.5000000
Figure 11(b) RML	0.2943029
Figure 11(c) Ph Mono	11.18456
Figure 13(a) RMONO	16.16871
Figure 13(b) RML	1.527310
Figure 13(c) Ph Mono	2.213950

RMSE IMPROVEMENT: RMONO: .80 RML: 7.35 Phase Mono:1.00

Bandwidth: 4 GHz and 5 frequencies

Figure 12(a) RMONO	0.3842366
Figure 12(b) RML	0.2840927
Figure 12(c) Ph Mono	15.98086
Figure 14(a) RMONO	0.2218391
Figure 14(b) RML	0.0000000E+00
Figure 14(c) Ph Mono	19.09178

RMSE IMPROVEMENT: RMONO: 58.45 RML: 61.74 Phase Mono:1.00

7. ACKNOWLEDGEMENTS

The authors acknowledge assistance provided by Jim Rody and Anna Wilkinson from Advanced Information Technology Inc.(AIT) as well as Titus Lo from McMaster University for processing the experimental data.

8. REFERENCES

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[2] Turner, R.M, Bossé, E., " Maximum Likelihood Tracking Using a Highly Refined Multipath Model ", 21st Asilomar Conf. on Signals, Systems and Computers, Pacific Grove, CA, Nov.2-4, 1987.

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[4] Lo, T., Litva, J., " Low-Angle Tracking Using a Multifrequency Sampled Aperture Radar: An Experimental Investigation ", IEEE Trans. on AES, vol.21, No.5, pp.797-805, Sept.1991.

[5] Kerr, D.E, ed., " Propagation of Short Radio Waves ", Peter Perigrinus, London, 1987.

[6] Bossé, E., Turner, R.M., Riseborough, E. S., " Model-Based Multifrequency Array Signal Processing for Low-Angle Tracking ", to appear in IEEE Trans. on AES, Vol. 30, No.4, Oct. 1994.

APPENDIX A

DETAILED DESCRIPTION OF THE DATA FILES

This appendix lists the data files, gives a detailed description of the information about the parameters used during the collection of the data and shows how to correct and calibrate the experimental data. Table A-1 lists the Lake Huron data files collected during the four days: Nov.1-4, 1987 by McMaster University. The names of the data files have been chosen according to the type of run. The terminology is defined as follows:

CFF far field/one horn over water calibration run

CIQ internal (in-phase and quadrature-phase) calibration run

DD dual polarizations (horizontal and vertical) transmission and horizontal polarization reception run

DH horizontal polarization transmission and horizontal polarization reception run

DV horizontal polarization transmission and vertical polarization reception run

Table A-2 lists the information stored in the preambles. The table contains 9 columns. The BLKS column indicates the relative size of the data file for the original unformatted data file. (1 block = 512 bytes) Records (=data sets) indicates the number of records or runs of a given time duration in one data file. The next column is the data file name followed by AGC0 and AGC1. AGC stands for Automatic Gain Control: 1 is for the agile frequency and 0 for the fixed frequency. This is a relative indication (no unit) of the transmitter power at each frequency. The SNAPS column gives the number of snapshots (instantaneous discrete time measurements of the antenna aperture) taken during a particular run or record. FREQ indicates the frequency flag identifier. Finally, Target indicates the relative target height with respect to a reference point 9.5 m above the water level.

The calibration performed by DREO is the "best" calibration possible under the prevailing circumstances. These circumstances are the obvious lack of information and the large number of errors in the experimental recordings. The errors discovered in these files are primarily the result of poor note taking or information recording in the preambles of the files. Very often the transmitting frequencies, the target heights, the number of data sets, ...etc, were not recorded. The data files not having this information were rejected from the data base. The Lake Huron calibration program developed by DREO will calibrate all the

records in a file. To do this, it requires an input file or a setup file containing all the important information of each record in that file.

The calibration software was developed on an IBM compatible computer using NDP Fortran compiler. The setup file is created by the LHURSET.EXP program which resides in the CALSET subdirectory. The *.dat and *.bak files are necessary for the proper execution of this program. The user simply chooses the file for which he wishes to create a setup file. When the setup file is complete the user runs LHURON.EXP and enters the name of the setup file created. The program receives its input and writes its output to the CALDAT subdirectory.

A record is defined as all the snapshots of both the fixed and agile frequencies for each run in a file. Thus if a run had 64 snapshots, the record would contain 64 snapshots * 32 elements/snapshots * 2 frequencies/element * 2 channels/frequency * 2 bytes/channel = 16384 bytes.

The fixed frequency is 10.2 GHz while the agile frequency varies from run to run. The frequency flag indicates what the agile frequency should be for each record according to Table A-3. In somes cases, the frequency flag is replaced by the picket number which indicates a particular frequency. As an example, picket number 59 means a frequency of 9.79 GHz according to Table A-3.

Figs. A-1 and A-2 show how the calibration procedure is to be done. An "IQ" calibration table must be created from one of the possible CIQ*.* files. Next, a far-field calibration table is created using the newly created "IQ" calibration table and one of the possible CFF*.* files. These two tables, "IQ" and "FF", are used to calibrate one of the D*.* files.

The following is a list of tables which are sufficient for the calibration of the Lake Huron data:

iqtable1.tbl	- low gain iq table
iqtable2.tbl	- high gain iq table
iqtable3.tbl	- high gain fixed freq, low gain agile
fftable1.tbl	- low gain ff table
fftable2.tbl	- high gain ff table
fftable3.tbl	- high gain fixed freq, low gain agile

There are two sets of three tables; one set is used for IQ correction and the other for FF (Far Field) calibration. iqtable1 and fftable1 are the calibration tables when AGC0 and AGC1 both take the value between 40-48. Ref. (A-1) gives a description of how these

values of AGC0 and AGC1 can be used to control the IF amplifiers. iqtable2 and fftable2 are used when AGC0 and AGC1 both take the value 84. Finally iqtable3 and fftable3 are used for an AGC0 of 84 while AGC1 is between 40-48. The results of the calibration are placed in EXP_FFC.DAT. This is an unformatted direct access file. An example of the read command is in read.exa.

The high gain IQ calibration table was produced from CIQ3.NV3 and the far field calibration table from CFF3.NV3. *Table 3 uses the fixed frequency of *Table 2 and the agile frequency of *Table 1, where *Table 1 is the low gain table and *Table 2 is the high gain table. Also for FF table use first data sets of CFF1.NOV2 (CIQ6.NOV2) and other remaining records of data sets of CFF6.NOV1 (CIQ6.NOV2) to make the proper calibration table.

[A-1] Lee K., Fines R., " MARS evaluation report ", Applied Silicon Inc., Ottawa, March 1991.

Table A-1
List of data file names

MARS_NOV1.BAK	MARS_NOV2.BAK	MARS_NOV3.BAK	MARS_NOV4.BAK
12 files	21 files	24 files	22 files
8573 blocks	9318 blocks	29088 blocks	22320 blocks
CFF1.DAT	CFF1.DAT	CIQ1.DAT	CIQ1.DAT
CFF2.DAT	CFF1A.DAT	CIQ2.DAT	CIQ1A.DAT
CFF4.DAT	CFF2.DAT	CIQ3.DAT	CIQ2.DAT
CFF5.DAT	CFF3.DAT	CIQ4.DAT	CIQ3.DAT
CFF5A.DAT	CFF3A.DAT	CIQ5.DAT	CIQ4.DAT
CFF6.DAT	CFF4.DAT	CIQ6.DAT	CIQ4A.DAT
CFF7.DAT	CIQ1.DAT	CIQ7.DAT	CIQ5.DAT
CIQ2.DAT	CIQ2.DAT	CIQ7A.DAT	CIQ6.DAT
CIQ3.DAT	CIQ3.DAT	CIQ8.DAT	CIQ7.DAT
CIQ4.DAT	CIQ4.DAT	CIQ85.DAT	CIQ8.DAT
CIQ5.DAT	CIQ4A.DAT	CIQ86.DAT	DH1.DAT
CIQ6.DAT	CIQ5.DAT	DD1.DAT	DH1B.DAT
	CIQ6.DAT	DD2.DAT	DH2.DAT
	CIQ7.DAT	DH1.DAT	DH3.DAT
	DD1.DAT	DH2.DAT	DH4.DAT
	DD2.DAT	DH3.DAT	DH5.DAT
	DD4.DAT	DH4.DAT	DH6.DAT
	DH1.DAT	DH5.DAT	DH61.DAT
	DH2.DAT	DH6.DAT	DH7.DAT
	DV1.DAT	DH7.DAT	DH8.DAT
	DV2.DAT	DH8.DAT	DH9.DAT
		DV1.DAT	DV1.DAT
		DV3.DAT	
		DV2.DAT	

Table A-2
Data File Names

MARS_NOV1.BAK								
Line	Blks	Recs	*.DAT	AGC0	AGC1	Snaps	Frequency	Target
1	1008	15	CFF1	40	48	127	FL1	0
2	648	9	CFF2	40	48	127	1 Horn Cal.	0
3	644	16	CFF4	84	84	64	1 Horn FL1	0
4	644	16	CFF5	84	84	64	FL2	0
5	41	1	CFF5A	84	84	64	REPEAT 58	0
6	644	16	CFF6	40	48	64	SIGNAL LOW FL1	0
7	644	16	CFF7	40	48	64	1 HORN CAL	0
8	644	16	CIQ2	40	48	64	LOCAL IQ CAL ARRAY ON TOWER	0
9	644	16	CIQ3	40	48	64	FL2	0
10	644	16	CIQ4	84	84	64	FL1	0
11	644	16	CIQ5	84	84	64		0
12	386	16	CIQ6	40	48	32	LOCAL IQ CAL	-7
13	386	16	TITUS1	40	48	32	LOCAL IQ CAL	car @ home
14	386	16	TITUS2	40	48	32	LOCAL IQ CAL	car @ 9.0m
15	386	16	TITUS3	40	48	32	LOCAL IQ CAL	car @ bottom (-7)

MARS_NOV2.BAK								
Line	Blks	Recs	*.DAT	AGC0	AGC1	Snaps	Frequency	Target
16	644	16	CFF1	45	48	64	1 Horn Cal F1 LOW SIG	-6.958
17	41	1	CFF1A	45	48	64	REPEAT PICKET 90	-6.958
18	644	16	CFF2	45	48	64	SIG LOW PICKET 77	-6.958
19	644	16	CFF3	84	84	64	FL1	-6.958
20	81	2	CFF3A	84	84	64	REPEAT 120&140	-6.958
21	644	16	CFF4	84	84	64	FL2	-6.958
22	242	6	CIQ1	45	48	64	LOCAL IQ CAL AGC0	8.991
23	41	1	CIQ2	45	48	64	Picket #1	-6.958
24	644	16	CIQ3	45	48	64	FL1	-6.958
25	644	16	CIQ4	84	84	64	FL1	0
26	81	2	CIQ4A	84	84	64	REPEAT 90 & 120	0
27	644	16	CIQ5	84	84	64	FL2	0
28	644	16	CIQ6	45	48	64	FL1	0
29	644	16	CIQ7	45	48	64	FL2	0
30	360	5	DD1	84	48	127	SIM DUAL POL 2-3 FT WAVES (70)	9.0, 8.5, 8.0, 7.5, 7.0
31	576	8	DD2	84	48	127	AGAIN CL1 Picket 70	9.0,6.0,3.5, 3.0,-3.03, -5.22,-6.0, -6.96
32	72	1	DD4	84	48	127	AGAIN CL1 Picket 70	9.0
33	363	9	DH1	45	48	64	FL3	3@9.0 3@0.0 3@-7.0
34	1329	33	DH2	45	48	64	??	DOTHGT= 9.0,-7.0, -0.5
35	242	6	DV1	84	84	64	FL3	3@9.0, 3@0.0
36	94	2	DV1A	84	84	64,9, 64	FL3	BOTTOM -6.96

MARS_NOV3.BAK								
Line	Blks	Recs	*.DAT	AGC0	AGC1	Snaps	Frequency	Target
37	1152	16	CIQ1	45	48	127	REG GAIN FL1 SR=62.5	0
38	1152	16	CIQ2	45	48	127	REG GAIN FL2	0
39	1152	16	CIQ3	84	84	127	HIGH GAIN FL1	0
40	1152	16	CIQ4	84	84	127	HIGH GAIN FL2	0
41	1152	16	CIQ5	45	48	127	REG GAIN FL1 SR=32.5	0
42	1152	16	CIQ6	45	48	127	SR=32.5 FL2	0
43	1152	16	CIQ7	84	84	127	HIGH GAIN FL1 SR=32.5	0
44	72	1	CIQ7A	84	84	127	REPEAT 144 FOR CIQ7	0
45	1152	16	CIQ8	84	84	127	HIGH GAIN FL2 SR=32.5	0
46	1152	16	CIQ85	45	48	127	REG GAIN FL1	9.0
47	1152	16	CIQ86	45	48	127	REG GAIN FL2	9.0
48	2376	33	DD1	84	48	127	SIM DUAL POL 2-3 FT WAVES (70) CL3	DOTHGHT =9.0, -7.0, -0.5
49	2376	33	DD2	84	48	127	SR=31.25 CL3 (70)	DOTHGHT =9.0, 7.0, -0.5
50	1152	16	DH1	45	48	127	FL1	BOTTOM (-7.0)
51	1152	16	DH2	45	48	127	FL1	@BOTTOM (-7.0) PICKET 60
52	1152	16	DH3	45	48	127	FL1	@ TOP
53	1152	16	DH4	45	48	127	REPEAT DH3	@ TOP
54	1224	17	DH5	45	48	127	FL1 (120x2)	@ HOME
55	1152	16	DH6	45	48	127	FL2	@ HOME
56	1152	16	DH7	45	48	127	FL1	-5.22
57	1152	16	DH8	45	48	127	FL1	-6.5
58	1152	16	DV1	84	84	127	FL1	@BOTTOM (-7.0)
59	1152	16	DV2	84	84	127	REPEAT	REPEAT (-7.0)
60	1152	16	DV3	84	84	127	FL1	0 m

MARS_NOV4.BAK								
Line	Blks	Recs	*.DAT	AGC0	AGC1	Snaps	Frequency	Target
61	1152	16	CIQ1	45	48	127	REG GAIN FL1 IQ CAL	0
62	1152	16	CIQ1A	45	48	127	REPEAT CIQ1.NV4	0
63	1152	16	CIQ2	45	48	127	REG GAIN FL2	0
64	1152	16	CIQ3	84	84	127	HIGH GAIN FL1 IQ CAL	0
65	1152	16	CIQ4	84	84	127	HIGH GAIN FL2	0
66	72	1	CIQ4A	84	84	127	REPEAT PICKET 37 FOR CIQ4.NV4	0
67	1152	16	CIQ5	45	48	127	REG GAIN FL1 SR=31.25	0
68	1296	18	CIQ6	45	48	127	LOCAL CAL FL1 +58, +59	0
69	1296	18	CIQ7	45	48	127	FL1, +58 +59	0
70	1152	16	CIQ8	84	84	127	HIGH GAIN FL1	0
71	1152	16	DH1	45	48	127	FL1	0
72	1152	16	DH1B	45	48	127	REPEAT DH1.NV4	0
73	1152	16	DH2	45	48	127	FL1	3.03m
74	1152	16	DH3	45	48	127	FL1	3.03m
75	144	2	DH4	45	48	127	58, 59	3.03m
76	1296	18	DH5	45	48	127	FL1, +58, +59	-5.22m
77	1296	18	DH6	45	48	127	FL1, +58, +59	-6.0m
78	144	2	DH61	45	48	127	SR=31.25 1,144	-6.0m
79	1296	18	DH7	45	48	127	FL1*, 80,58,59 (*=missed 80)	BOTTOM -6.951m
80	1296	18	DH8	45	48	127	FL1,58,59	+3.529m
81	1296	18	DH9	45	48	127	FL1,58,59	+6.0m
82	216	3	DV1	84	84	127	1,70,70 or more likely 1,70,144	-3.03m

Table A-3
Definition of the frequency flags

Frequency Lists
FL1: 1,10,20,...130,140,144
FL2: 1,9,14,37,47,50,58,59,77,84,101,116,130,132,136,144
FL3: 1,70,144
FL4: 1,2,3,4,...142,143,144 (not used)

Frequency Conversion

$$f = 8.02 \text{ GHz} + (FL\# \times 0.030) \text{ GHz}$$

e.g. FL# = 1 --> f=8.05 GHz
FL# = 10 --> f=8.32 GHz
FL# = 9 --> f=8.29 GHz

Record	FL1	f(GHz)	FL2	f(GHz)	FL3	f(GHz)
1	1	8.05	1	8.05	1	8.05
2	10	8.32	9	8.29	70	10.12
3	20	8.62	14	8.44	144	12.34
4	30	8.92	37	9.13		
5	40	9.22	47	9.43		
6	50	9.52	50	9.52		
7	60	9.82	58	9.76		
8	70	10.12	59	9.79		
9	80	10.42	77	10.33		
10	90	10.72	84	10.54		
11	100	11.02	101	11.05		
12	110	11.32	115	11.50		
13	120	11.62	130	11.92		
14	130	11.92	132	11.98		
15	140	12.22	136	12.10		
16	144	12.34	144	12.34		

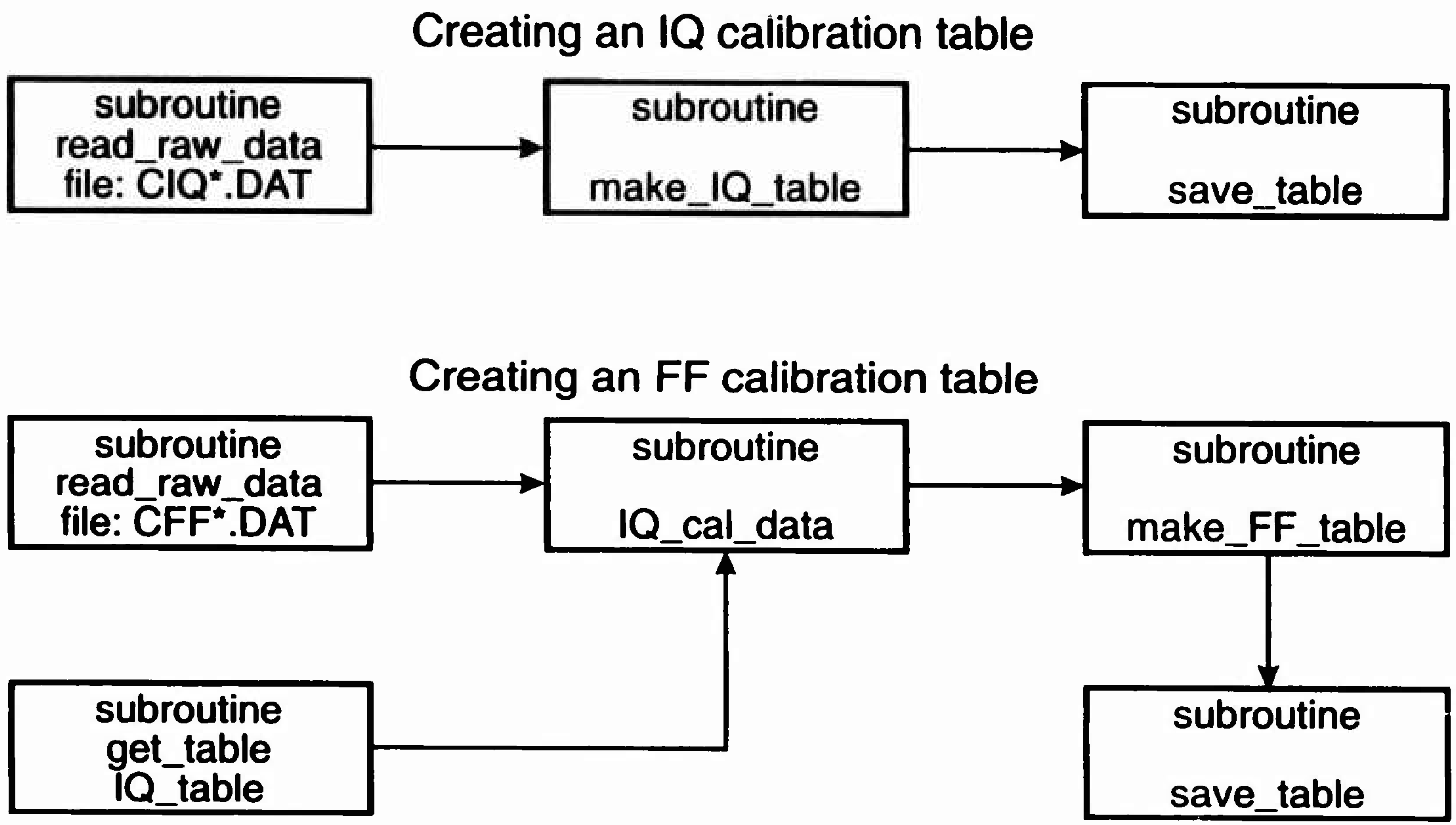

Figure A-1. Chart I Creating Calibration Tables.

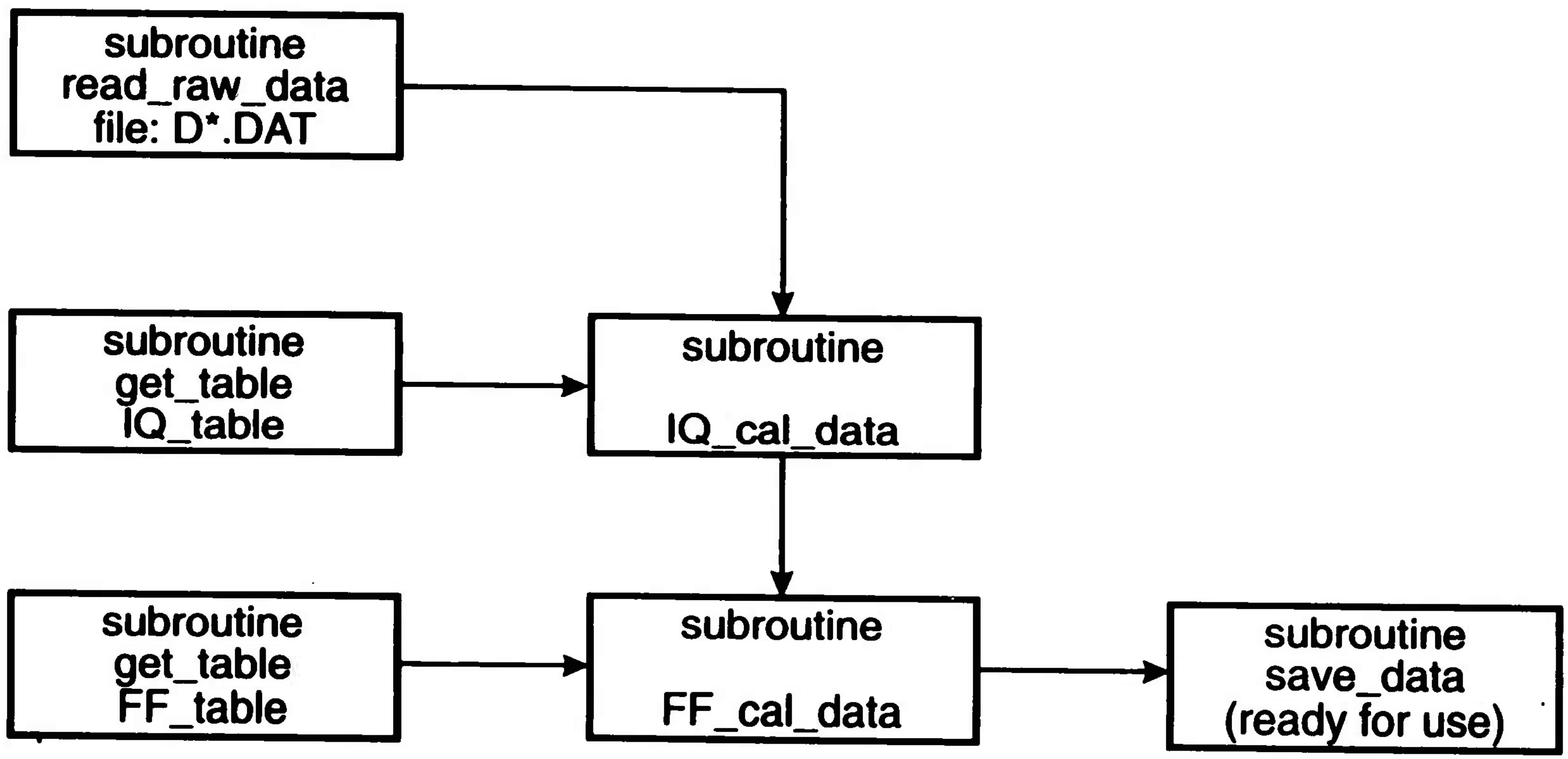

Figure A-2. Chart II Calibrating Raw Data.

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The Lake Huron Data Base: Characterization and Use for Evaluating Multifrequency Monopulse Tracking Using a Multipath Propagation Model (U)

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This report has two objectives: (1) to describe in detail a unique multifrequency (8-12 GHz) 32-element array data base collected over Lake Huron, and (2) to investigate the experimental performance of multifrequency phase monopulse using a model for specular multipath (called refined monopulse or RMONO because of its use of a "refined" propagation model). Tracking performance is compared with that obtained with phase monopulse averaged over the frequency agile bandwidth and with that obtained with the Refined Maximum Likelihood (RML) algorithm. The results show that for wide agile bandwidth (4 GHz centred on 10 GHz) and adequate number of frequencies (5), RMONO performs almost as well as RML and both perform much better than phase monopulse. However, phase monopulse compares more favorably with a smaller bandwidth (2 GHz) and fewer frequencies (3).

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Radar, low angle tracking, multipath